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Computer Simulation of Airborne Circular Array Radar Data

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A computer code for simulating airborne circular array radar data was developed at NRL. The code models non-stochastic target signals plus stochastic clutter, jammer, and noise signals. The code is able to model arbitrary radar waveforms and arbitrary antenna element patterns. An important feature of the code is the capability to model the radially outward orientation of the receive elements. The output consists of signal samples at each receive element, for each range bin, for each pulse return. Multiple independent realizations of the stochastic signal types can be generated. Simulated data generated using this code will be used to support the development of signal processing algorithms for use with airborne circular array radars.

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COMPUTER SIMULATION OF AIRBORNE CIRCULAR ARRAY RADAR DATA

INTRODUCTION

The current generation of airborne surveillance radars employs mechanically scanned, linear array antennas. The TRAC-A is an example of such an antenna. An alternative antenna design considered for future deployment is the electronically steered circular array. Advantages associated with this antenna design include the elimination of moving parts such as motors and slip rings, as well as an enhanced track while scan capability. However, it is expected that circular array data will have distinctive properties and characteristics that distinguish these data from linear array data. For this reason, efforts to analyze and assess circular array radar designs and associated signal processing algorithms via computer simulation will require access to either measured circular array data or the availability of high fidelity simulated circular array radar data. This report describes new computer software developed for generating high fidelity simulated airborne circular array radar data suitable for use in computer simulations.[1]

Because of differences in the positioning of the array elements and because of differences in the orientations of the array elements, circular array data will have properties and characteristics that distinguish these data from linear array data. Consider an airborne linear array, oriented horizontally, scanning for targets just above and below the horizon over 360 degrees in azimuth. Defining the vertical plane perpendicular to the axis of the array as the boresight azimuth plane, signals arriving from anywhere in this plane will arrive in phase at all array elements. As a consequence, a linear array can be steered in the direction of the boresight azimuth plane by sampling the array elements simultaneously and combining those samples without the application of phase shifts or time delays. Ground clutter returns from the boresight azimuth plane arrive in phase at all array elements regardless of range. As a consequence, the element-to-element clutter covariances for linear arrays are relatively constant with respect to range. This is of importance for certain signal processing algorithms which rely on estimates of the clutter covariance matrix for a particular range, made by averaging measurements made over some range window.

Now consider an airborne circular array, oriented horizontally, scanning for targets just above and below the horizon, over 360 degrees in azimuth. There is no direction of interest from which signals will arrive in phase at all array elements. As a consequence, it is necessary to employ non-simultaneous sampling, or to apply time delays or phase shifts to the signal samples to steer the array. Also, the relative phase of ground clutter returns at the different elements of a horizontal circular array depends on the range to the clutter patch. The phase difference is a maximum for clutter patches at the horizon. This results in the relative non-stationarity of clutter covariances with range.

With regard to the relative orientations of the elements, all elements in a linear array point in the same direction; towards boresight azimuth. In a circular array the elements point radially outward rather than in

[1] This work was sponsored by the Office of Naval Research, contract no. N0001400WR20158.

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the same direction. Therefore only one receive element can point in the direction of the transmit antenna beam. One consequence of this is diminished receive antenna gain as compared to a comparable linear array. Another consequence is a more complicated clutter covariance matrix. This results from the fact that each receive element "sees" two non-overlapping clutter footprints; one associated with the receive element pattern and the other associated with the transmit antenna pattern.

SIMULATION OVERVIEW

The new software described in this report fully accounts for the circular positioning of the array elements. It does this through the use of vectors to specify the positions of the transmit antenna and of the individual receive array elements. The software also fully accounts for the radial orientation of the array elements. It does this through the use of matrices to specify the orientations of the transmit antenna and of the individual receive elements. Simulated data generated using this new software can be expected to exhibit the properties and characteristics of measured circular array data.

The radar is modeled as a single "effective" transmit antenna element, and multiple independently sampled receive antenna elements. The positions, orientations, and velocities of the "effective" transmit antenna and of the receive antenna elements can be specified arbitrarily. Thus the software can model not only circular arrays but arrays of arbitrary geometry. For simulating circular array data the following defaults can be invoked. All elements (transmit and receive) lie in a horizontal plane and are oriented horizontally. The circular array is initially centered directly above the origin with the phase center of the transmit antenna at the center of the array. The array is directed towards the target. This means that the transmit antenna points in the direction of target azimuth and only one-half of the receive elements, those pointing within 90° of target azimuth, are considered active. This is illustrated schematically in Figure 1.

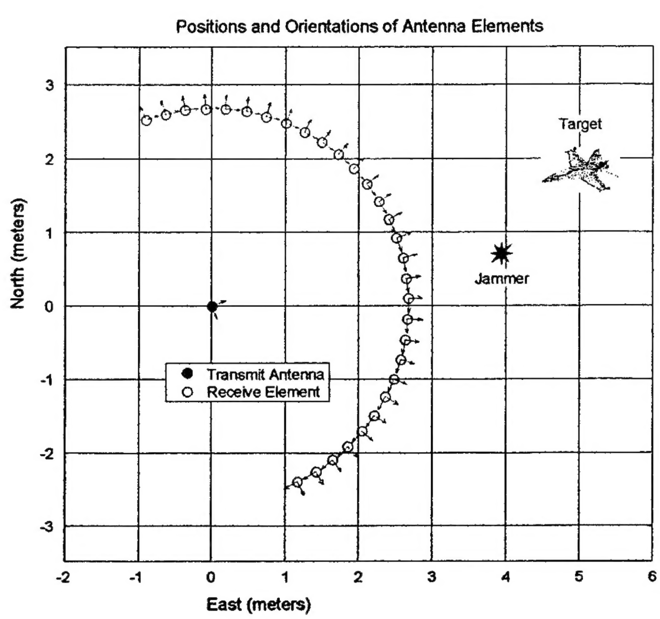

Fig. 1 – Circular array geometry

The solid circle at the origin of Figure 1 indicates the position of the phase center of the transmit antenna. The open circles indicate the positions of the phase centers of the active receive antenna

elements. The icons labeled "Target" and "Jammer" indicate target and jammer azimuth. (Their ranges are too large for the target and jammer positions to be plotted on the same scale that shows the positions of the array elements.) The small green arrows overlaying the transmit antenna and the receive elements indicate the directions (in the horizontal plane) in which those elements are pointing. It can be seen that the transmit antenna points in the direction of the target azimuth. Similarly, the active portion of the receive array consists of those elements pointing within 90° of target azimuth. Platform and target velocities are accounted for by recomputing the positions of the array and of the target every pulse repetition interval.

The software simulates target, clutter, jammer and noise signals. The target return signal at each receive element is modeled as a delayed and scaled replica of the transmitted signal. This is implemented by specifying the transmitted radar waveform via an analytic expression, $f(t)$. The default $f(t)$ is of the form: $f(t) = \begin{cases} e^{j\omega t} & 0 < t < D \\ 0 & Otherwise \end{cases}$

where ω is the radar center frequency in radians and D is the pulse duration. The default expression for $f(t)$ can be overridden and an arbitrary wideband waveform modeled instead. The target return signal at the i^{th} receive element channel is modeled as $\gamma_i f(t-\tau_i)$ where the delay, τ_i, is given by the total path length traversed by the signal, divided by the speed of light. The scaling factor, γ_i, takes into account such factors as transmitted power, target RCS, target range, and transmit and receive antenna pattern factors. The target signal is modeled as deterministic and only a single realization of the target signal is generated for a given scenario. The clutter signal at each receive element is modeled as the superposition of returns from a collection of unresolved, moving, point scatterers. The clutter is modeled as stochastic. Different realizations of the clutter signal are generated by choosing different initial positions and velocities for the scatterers. In an analogous manner, the jammer signal at each receive element is modeled as a delayed and scaled replica of a modeled jammer emission waveform. The jammer signal is modeled as stochastic. Different realizations of the jammer signal are generated by choosing different jammer emission waveforms all having the same average power. The noise signals at each receive element channel are modeled as random processes.

The output of the simulation consists of samples of each of the four signal types, for each receive antenna element channel, for each range bin in the range window, over a dwell encompassing several pulse repetition intervals (pri). The samples of the four signal types are stored on separate files. Linear combinations of the simulated data stored in these files can then be formed. By adjusting the weights used in forming the linear combinations, the power ratios of the various signal types in the combined data can be varied without re-executing the simulation software. In particular, if the target signal is given zero weight in the linear combination, the radar is effectively scanning in a direction in which there is no target.

The computation of path delays is facilitated by the use of vectors to specify the positions of all scatterers, jammers, the phase centers of an "effective" transmit antenna, and of all receive antenna elements. These vectors are represented in an earth-fixed coordinate system. A line-of-sight vector from an antenna element to a scatterer or jammer can be constructed by taking the (vector) difference between the respective position vectors. One way path lengths are given by the lengths of these line-of-sight vectors. Path delays and path losses are computed from the path lengths.

Antenna pattern factor refers to the transmit antenna gain in the direction of a scatterer, or the gain of a receive antenna element in the direction of a scatterer or jammer. Antenna pattern factor depends on the antenna gain pattern and on the direction of the line-of-sight from the element to the scatterer or jammer. Antenna gain patterns are specified for the transmit antenna and for each receive element in local, element-fixed coordinates. Line-of-sight vectors are computed in earth-fixed coordinates. Associated with each

element is a *3x3* transformation matrix which is used to transform line-of-sight vectors from earth-fixed to local, element-fixed coordinates. The rows of the transformation matrix for an element are unit vectors in the principal directions of that element, expressed in earth-fixed coordinates. The principal directions of an element are *90* degrees local azimuth, zero degrees local elevation; zero degrees local azimuth, zero degrees local elevation; and zero degrees local azimuth, *90* degrees local elevation, respectively. Thus the spatial orientation of each element is specified by its transformation matrix.

A block diagram illustrating the computation of the simulated data is shown in Figure 2. Separate processing paths are used to generate target, clutter, jammer, and noise signals. The output from each processing path is formatted into an *NMxK* array where *N* is the number of receive antenna elements, *M* is the number of pulses, and *K* is the number of range bins. Typical values for *N*, *M* and *K* are *30* antenna elements, *16* pulses, and *1000* range bins respectively. Thus a typical array would have dimensions *480 x 1000*. The simulation software generates a single realization of the non-stochastic target signal, and multiple realizations of the stochastic jammer, clutter and noise signals. This is indicated in Figure 2 by the '**Script*' files in which the '**Run*' files are embedded, and by the multiple '**Dat*' outputs.

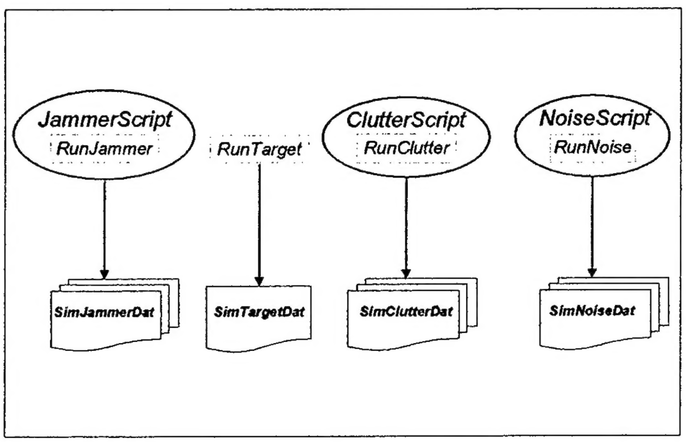

Fig. 2 – Block diagram illustrating the four processing paths for the four signal types

Target Signal

A block diagram indicating the routines used in the computation of the simulated target data is shown in Figure 3. This basic software building block computes target return signal samples by evaluating the analytic expression for the transmitted radar waveform for particular input values, and then scaling the result. The scaling factors depend on radar power, target RCS, range, and transmit and receive antenna pattern factors. Antenna pattern factors are computed once, at the beginning of the dwell, and treated as constants over the dwell. The input values for which the radar waveform analytic expression is evaluated depend on the sample times and on the path delays. The path delays are computed from the geometry at the start of each pulse repetition interval. The change in the path delays from pulse to pulse is determined by platform velocity, target velocity, and radar pri. Platform and target Doppler are accounted for by changes in path delays from pulse to pulse. Simulation of the target signal is discussed in more detail in Schutz [1], [2].

Simulated data are generated for a range window having a target at the center of each range bin. The slant range to the center of the innermost range bin and the number of range bins in the range window are

specified. A target azimuth, height, and velocity are specified. The targets in each of the range bins all have the same height and azimuth, and move with the same velocity. The default option has the transmit antenna and the active portion (one-half of the elements) of the receive antenna array pointing in the direction of target azimuth. The different signal types are generated and stored independently. Therefore simulated data not containing a target signal can be generated by not incorporating the target return signal into the combined data. The default option can be overridden and the transmit antenna and receive array pointed in arbitrary directions, not necessarily in the direction of the target. This option is available for use in studies of target location accuracy.

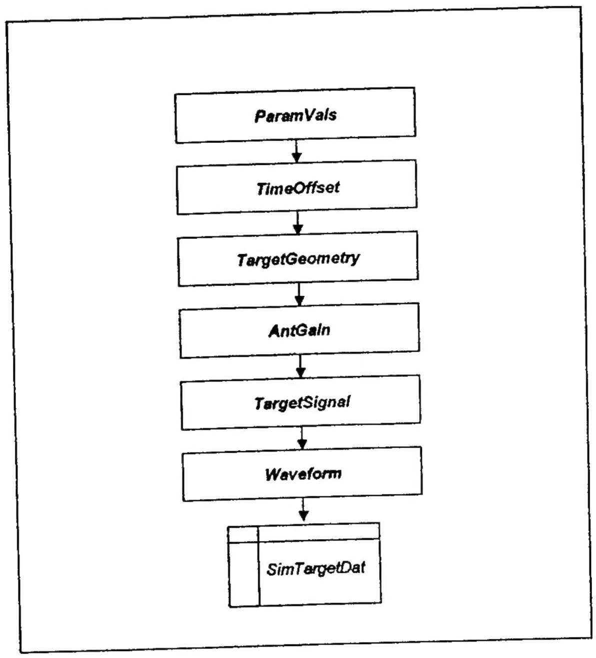

Fig. 3 – Target signal processing path

The initial positions, orientations and velocities (speed and direction) of the transmit antenna and receive antenna elements are entered into the MATLAB workspace by the routine *ParamVals*. Target height, azimuth, and velocity are also entered into the MATLAB workspace. The slant range to the innermost range bin and the number of range bins in the range window are also input. The routine *ParamVals* computes the coordinates of a target in each range bin at the height and azimuth specified. The routine *TimeOffset* computes path delays $T_{n,k}$ for the initial positions of the transmit antenna, receive antenna elements, and targets; where n refers to the receive antenna, and k refers to the target range bin. Routine *TargetGeometry* updates the positions of the transmit antenna, receive antenna elements and targets at the start of each pri and computes the path delays $\tau_{n,m,k}$ for all pri's in the dwell, where n refers to the receive antenna element, m refers to pulse index, and k refers to target range bin. Routine *AntGain* computes transmit and receive antenna pattern factors at the start of the dwell. Routine *TargetSignal* evaluates the analytic expression for the radar waveform, $f(t)$, for $t = (T_{n,k}-\tau_{n,m,k}+D/2)$. Function *Waveform* contains the analytic expression for the radar waveform. The simulated target data samples are stored in file *SimTargetDat*.

The matrix specifying the orientation of the transmit antenna is computed in routine *ParamVals* and is such that the transmit antenna points in the direction of the target azimuth. The routine *ParamVals* also

determines which array elements are at azimuths closest to the target azimuth. Simulated data are generated only for these elements. The receive array is time delay steered in the direction of target azimuth. This is implemented by evaluating the radar waveform at times $t = (T_{n,k} - \tau_{n,m,k} + D/2)$. This corresponds to sampling the n^{th} array element at time $(T_{n,k}+D/2)$ or, equivalently, applying time delays $(\mathscr{T} - T_{n,k} - D/2)$ to the receive element channels and sampling all channels simultaneously at time $\mathscr{T}$. Note that $T_{n,k}$ refers to path delays with respect to the target. Signals arriving from directions other than the target direction will have path delays different from the target. Therefore $(T_{n,k} - \tau_{n,m,k} + D/2)$ will not, in general, be equal to $D/2$ at all receive element channels and the non-target signal samples at those elements will not, in general, be in phase. Also, $T_{n,k}$ is computed for, and refers to the first pulse return. The phase of the target signal samples will be different from pulse to pulse because $\tau_{n,m,k}$ changes from pulse to pulse as a result of platform and target motion. The phase of the target signal samples will, however, be the same from element to element for all pulse returns. This reflects the fact that the receive array is time delay steered in the direction of the target, which is also the direction of the transmit antenna beam. The individual receive elements are not steered. Their orientation is fixed such that they point radially outward.

```
» SimTargetDat(1:5,1:4)

ans =

  1.0e-011 *

   0.0269 - 0.0000i   0.0269 - 0.0000i   0.0269 - 0.0000i   0.0269 - 0.0000i
   0.2975 - 0.0000i   0.2974 + 0.0000i   0.2972 - 0.0000i   0.2970 - 0.0000i
   0.3254 - 0.0000i   0.3252 - 0.0000i   0.3250 - 0.0000i   0.3248 - 0.0000i
   0.3526 - 0.0000i   0.3524 - 0.0000i   0.3522 - 0.0000i   0.3520 - 0.0000i
   0.3789 - 0.0000i   0.3787 - 0.0000i   0.3785 - 0.0000i   0.3783 - 0.0000i

» SimTargetDat(31:35,1:4)

ans =

  1.0e-011 *

   0.0256 - 0.0083i   0.0256 - 0.0083i   0.0256 - 0.0083i   0.0256 - 0.0083i
   0.2830 - 0.0919i   0.2828 - 0.0919i   0.2826 - 0.0918i   0.2825 - 0.0918i
   0.3095 - 0.1005i   0.3093 - 0.1005i   0.3091 - 0.1004i   0.3089 - 0.1003i
   0.3354 - 0.1089i   0.3352 - 0.1089i   0.3350 - 0.1088i   0.3348 - 0.1087i
   0.3604 - 0.1171i   0.3602 - 0.1170i   0.3600 - 0.1169i   0.3598 - 0.1169i

» SimTargetDat(61:65,1:4)

ans =

  1.0e-011 *

   0.0218 - 0.0158i   0.0218 - 0.0158i   0.0218 - 0.0158i   0.0218 - 0.0158i
   0.2407 - 0.1749i   0.2406 - 0.1748i   0.2404 - 0.1747i   0.2403 - 0.1746i
   0.2632 - 0.1913i   0.2631 - 0.1911i   0.2629 - 0.1910i   0.2628 - 0.1909i
   0.2853 - 0.2073i   0.2851 - 0.2071i   0.2849 - 0.2070i   0.2848 - 0.2069i
   0.3066 - 0.2227i   0.3064 - 0.2226i   0.3062 - 0.2225i   0.3060 - 0.2223i
```

Fig. 4 – Example of simulated target data

Shown in Figure 4 is an example of simulated target data. The data are stored in MATLAB binary format. These particular data are excerpted from file *'SimTargetDat100Km.dat'* which covers a range window containing *1000* range bins extending outward from *100 Km* in slant range. Only simulated data corresponding to the innermost four range bins are shown. The dwell consists of *16* pulses of which portions of three are shown. The receive antenna array consists of *30* elements of which only data from five are shown. The data are complex valued and represent in-phase and quadrature samples. The k^{th} column contains data corresponding to the k^{th} range bin. The first *30* rows of data correspond to target signal samples at the *30* receive elements for the first pulse repetition interval. Specifications (position, velocity, orientation) for the receive array elements are entered into the MATLAB workspace as the

3-dimensional array '*ReceiveGeom*' in routine '*ParamVals*'. Specifications for the n^{th} receive element are stored in the n^{th} page (third index equal to n) of that array. The m^{th} group of *30* rows corresponds to the m^{th} pulse return.

The first five rows of three groups of 30 rows are shown in Figure 4. These data correspond to the target signal samples at five receive elements for the first three pulses in the dwell. It should be noted that the samples at each element for the first pulse all have the same phase. This results from the fact that time offsets were introduced such that each element samples the midpoint of the first returned pulse. The change in the phase of the samples at each element from pulse to pulse results from the fact that the platform and target are moving and that the path distances and delays change from pulse to pulse. Simulated signal samples for the other three signal types are stored in the same format. The individual data types can be individually scaled before being added together. In this way the ratios of the powers of the various signal types in the combined signal can be varied without the necessity of re-executing the simulation code.

Clutter Signal

The clutter signal is modeled as the superposition of returns from a collection of unresolved, moving, identical point scatterers. The default geometry consists of a ring of scatterers in each range bin, spaced uniformly in azimuth. The individual scatterer ranges are drawn from a Gaussian distribution with mean value equal to the slant range to the center of the range bin. The scatterer velocities are radial with magnitudes drawn from a zero mean Gaussian distribution. The individual clutter scatterer signal samples are computed in exactly the same way target signal samples are computed. The sampling is performed at times $T_{n,k}$ (using the initial target range delays for each range bin). The transmit antenna pattern factor is computed for the transmit antenna pointed towards the target (not the scatterer). The receive antenna pattern factors are computed for each receive element pointing radially outward. The returns are sampled and then combined to form the clutter signal. The radial motions of the clutter scatterers result in the decorrelation of the clutter signal from pulse to pulse. Different realizations of the stochastic clutter signal are generated by choosing a different set of initial radial positions and speeds of the scatterers. A set of calibration runs is performed to set the scatterer RCS to achieve the specified clutter power. The clutter power can also be controlled by scaling the clutter signal before combining it with the target, jammer and noise signals.

Jammer Signal

Jammers are modeled as broadband barrage jammers. The Jammer signal differs from the target and clutter signals in that jammer signal is not an echo of a transmitted pulse. Because absolute path delays to a jammer cannot be measured, the jammer signal contains no range information. However, the difference in the path delays from the jammer to the different receive elements can measured and contains direction of arrival information. The jammer model has the jammer signal uncorrelated over time intervals equal to or longer than the time interval between range samples (i.e. uncorrelated from range sample to range sample and from pulse sample to pulse sample). The jammer emission waveform, over short time intervals (the time required to cross the array), is modeled as a sinusoid: $f(t) = Ae^{j(\omega t+\phi)}$ where ω is the radar center frequency, and A and ϕ are modeled as independent random variables. The simulated jammer signal sample for the n^{th} receive element, m^{th} pulse repetition interval, k^{th} range bin sample time, is computed by evaluating $f(t)$ at $t = (T_{n,k}-\tau_{n,m,k}+D/2)$, where $(T_{n,k}+D/2)$ is the time at which the element channel is sampled, and $\tau_{n,m,k}$ corresponds to the one way path delay from the element to the jammer. In the context of the jammer signal, the subscript k has no meaning (It is not necessary to model a jammer in each range bin). The subscript m denotes the pulse repetition interval to which the sample refers. This is

of no consequence in the context of the jammer since the jammer signal is uncorrelated from pri to pri. The sampled value is then scaled by the antenna pattern factor. Different realizations of the stochastic jammer signal are generated by choosing different sets of random phases and amplitudes for the jammer waveform sinusoids.

Noise Signal

The noise signal modeled has the noise uncorrelated from receive element to receive element, from range bin to range bin and from pulse to pulse. The noise signal samples are generated by drawing in phase and quadrature samples from a zero mean Gaussian distribution. The noise signal is scaled before combining with the target, jammer, and clutter signals.

CONCLUSIONS

Computer software for simulating airborne circular array radar data has been developed. This software is, in fact, able to simulate radar data for arbitrary array geometries, with circular array geometry being a special case. The software models the radar signal at each receive element channel as the superposition of a non-stochastic target signal with stochastic clutter, jammer and noise signals. The target and clutter return signals are modeled as scaled and delayed replicas of the transmitted waveform. The jammer signal is modeled as a scaled and delayed replica of a jammer emission waveform. The use of displacement vectors to specify the positions of the transmit antenna, receive antenna elements, targets, clutter scatterers, and jammers facilitates the computation of path delays. The use of transformation matrices to specify the antenna orientations facilitates the computation of antenna pattern factors.

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